Published online May 31, 2006

Estimating Yields of Salt- and Water-Stressed Forages with Remote Sensing in the Visible and Near Infrared

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ABSTRACT

In arid irrigated regions, the proportion of crop production under deficit irrigation with poorer quality water is increasing as demand for fresh water soars and efforts to prevent saline water table development occur. Remote sensing technology to quantify salinity and water stress effects on forage yield can be an important tool to address yield loss potential when deficit irrigating with poor water quality. Two important forages, alfalfa (*Medicago sativa* L.) and tall wheatgrass (*Agropyron elongatum* L.), were grown in a volumetric lysimeter facility where rootzone salinity and water content were varied and monitored. Ground-based hyperspectral canopy reflectance in the visible and near infrared (NIR) were related to forage yields from a broad range of salinity and water stress conditions. Canopy reflectance spectra were obtained in the 350- to 1000-nm region from two viewing angles (nadir view, 45° from nadir). Nadir view vegetation indices (VI) were not as strongly correlated with leaf area index changes attributed to water and salinity stress treatments for both alfalfa and wheatgrass. From a list of 71 VIs, two were selected for a multiple linear-regression model that estimated yield under varying salinity and water stress conditions. With data obtained during the second harvest of a three-harvest 100-d growing period, regression coefficients for each crop were developed and then used with the model to estimate fresh weights for preceding and succeeding harvests during the same 100-d interval. The model accounted for 72% of the variation in yields in wheatgrass and 94% in yields of alfalfa within the same salinity and water stress treatment period. The model successfully predicted yield in three out of four cases when applied to the first and third harvest yields. Correlations between indices and yield increased as canopy development progressed. Growth reductions attributed to simultaneous salinity and water stress were well characterized, but the corrections for effects of varying tissue nitrogen (N) and very low leaf area index (LAI) are necessary.

Salinity and drought are major inhibitors to agronomic production. The ability of growers to quickly adopt management practices that address productivity hinge on timely and accurate assessments of factors that impede crop growth. Increased efforts to remotely detect the effects of salinity hazards and water stress for irrigation management are needed since few studies have quantitatively assessed the ability of remote sensing technology to characterize simultaneous water and salinity stress on plant yields.

Current remote methods for assessment and monitoring salinity hazards in field situations have included optical sensing and soil electromagnetic induction (EM) techniques, both capable of timely assessments. When coupled with geographical information systems and sophisticated soil sampling strategies, EM has been established as a reliable and useful tool to estimate soil salinity patterns of fields between cropping seasons (Corwin et al., 1999). Salinity measurements based on EM are usually taken on bare soil during periods between crops or during seedling establishment. Electromagnetic induction correlates similarly to high water content and soil textures whose particle size is related to water holding capacity. Thus, a high EM reading does not always correspond to saline conditions, unless the bulk conductivity is above some value unapproachable without salinity effects. Despite these interactions, the relationship between bulk soil conductivity (EC_a) based on EM and sugarbeet growth and yield has been successfully demonstrated (Kaffka et al., 2000).

Similarly, crop reflectance spectra can often be confounded by other factors. Recently, field-derived spectra of salinized soils and vegetation were found to be good indicators of irrigation-induced soil salinization (Dehaan and Taylor, 2002) where spectra were indirectly related to salinity by delineating the presence or absence of various salinity indicator species. They noted, however, that absence of these species did not necessarily indicate that non-saline conditions existed. Bare soil spectral evaluations delineate soil salinity by recognizing evaporite minerals such as gypsum, halite, bassanite, polyhalite, and bloedite when compared to non-saline soils (Dehaan and Taylor, 2002). In forage production, however, the ability to detect the effects of simultaneous salinity and water stress on yield is needed for a mono-cropped, fully developed canopy.

Significant effort has been invested in evaluating relations between plant leaf and canopy reflectance measurements and nutrition, stress agents, and pigment composition. Recent research has related remote spectral indices with nitrogen fertility (Bausch and Duke, 1996; Read et al., 2002; Jacobsen et al., 1998), plant pigments (Sims and Gamon, 2002; Tan et al., 2000; Blackburn, 1998, 1999), and stress induced by a host of factors including water (Peñuelas and Inoue, 1999; Peñuelas et al., 1997; Datt et al., 2003) and pathological agents (Steddom et al., 2003; Rinehart et al., 2002).

Irrigation water management may address salinity stress detected indirectly by remote sensing of biomass reductions (Pinter et al., 2003), provided that a priori knowledge of the relationship between crop salinity

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Published in J. Environ. Qual. 35:1060–1071 (2006).
Technical Reports: Plant and Environment Interactions
doi:10.2134/jeq2005.0204

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Abbreviations: EC, electrical conductivity; ET, evapotranspiration; ETR, evapotranspiration ratio; LAI, leaf area index; NDVI, normalized difference vegetation index; NIR, near-infrared spectral region; R, canopy reflectance; VI, vegetation index; VLS, volumetric lysimeter system.

levels and crop reflectance or calibrations are provided. The use of photographic and videographic techniques to estimate cotton response to salinity was investigated by Wiegand et al. (1994). In their study, NDVI was defined as a function of integrated regions of NIR, red, and green regions based on either infrared film or videography. They found a good correlation ($r^2 = 0.72$) between an NDVI and lint yield converted from observations of cotton boll density. They defined the NDVI = (NIR − RED)/(NIR + RED) in waveband (RED = 600–700 nm for photos and 644–656 nm for video and NIR = 750–900 nm for photos and 845–857 nm for video) regions captured from digital imaging of photographs or video. Regression equations were also developed relating electromagnetic induction data in the surface 30 cm with digital counts in the RED, NIR, and GREEN (500–600 nm for photos and 543–552 nm for video). The authors offered no explanation for finding variation in yields and crop heights that were not always consistent with higher salinities recorded with EM. Carter (1993) identified similar visible wavelengths in the green-red region (535–640 nm) and in the red region (685–700 nm) that were sensitive to various types of stress (e.g., competition, herbicide, pathogens, dehydration) on six vascular plant species (loblolly pine, golden euonymus, slash pine, live oak, persimmon, and switchcane). With these remote indices, Carter and Young (1993) successfully characterized stress on a barrier island off the coast of Mississippi where salinity was present, but response in the visible wavelengths to stress was similar among agents and species. In soybean (Wang et al., 2002b) and elephant grass (Wang et al., 2002a) it was shown that biomass reductions due to salinity stress were highly correlated with a single ratio vegetation index (SRVI) in the NIR-red region. In both studies, Wang et al. (2002a, 2002b) reported reductions in reflectance in the NIR with increasing salinity stress and, for soybean this decrease was attributed to a greater specific leaf mass caused by salinity. However, they found no salinity effect in the visible domain.

Isolating salinity as the only factor influencing crop height and yield with remote indices is an ultimate goal. Managing the confounding effects of many stress agents that influence plant reflectance spectra continues to provide a major challenge. Spectra relating corn N and chlorophyll concentrations were confounded and weakened when subjected to prolonged water stress (Schepers et al., 1996). Water stress caused reflectance values of corn at 550 nm to become insensitive to changes in tissue N, yet at 850 nm the previously insensitive N region became sensitive to changes in N. It would seem logical to expect salinity and drought effects on leaf reflectance and yield to also be confounded by tissue N status. Additionally, the question of whether salinity and water stressed plants have similar reflectance spectra has not been thoroughly tested. As a first attempt, it may be possible to isolate, or at least integrate, the effects of N, water, and salinity stress into a remote estimation of crop yields.

Canopy reflectance indices that could be applied to different species would also be more useful than crop specific detection of salinity, water stress, and N effects. However, few studies have compared different crops under conditions where all three stressors were measured. Sims and Gamon (2002) reported that a structurally independent plant index, SIPI, developed by Peñuelas and Inoue (1999), was a pigment-related index calculated from the first derivative of the red edge (near 700 nm) region that was insensitive to canopy architecture, indicating that the same index should perform satisfactorily on different species.

Accurate ground truth measurements of combined salinity and water stress are essential when evaluating the applicability of remote sensing to estimate yield potential for a given species under these two stresses simultaneously. The objective of this study was to identify and establish vegetation indices, based on canopy reflectance in the visible and near-infrared (NIR) at two different sensor angles, that may estimate salinity and drought effects on canopy development and yield of alfalfa and tall wheatgrass forages.

MATERIALS AND METHODS

Experimental Treatments

The experiment was conducted from early spring to late fall, 2003, in Riverside, CA.

Six salinity treatments (EC_{iw} = 3, 8, 13, 18, 23, and 28 dS m^{-1}) were used to irrigate alfalfa (cv. Salado) and tall wheatgrass (cv. Jose) crops at different percentages of baseline evapotranspiration (ET_0). These forages were identified as moderately tolerant (alfalfa) and tolerant (tall wheatgrass) crops suitable for sequential water reuse systems where salinity has been identified as a potential problem (Grattan et al., 2004). Drought treatments were established by multiplying ET_0 by the following ET ratios (ETR = 0.5, 0.75, 1.0, 1.25), superimposed on the salinity stress treatments in an outdoor volumetric lysimeter system or VLS (Poss et al., 2004). The VLS consisted of twenty-four 1.4-m^3 concrete boxes filled with washed river sand (sand tanks) that had automated irrigation frequency and duration and recorded irrigation and drainage volumes, electrical conductivity, soil temperature, and soil moisture tension. The VLS used a flood irrigation method that maximized uniformity of application by delivering a thin film of water across the plot. The VLS measured cumulative evapotranspiration (ET) for each unit by taking the difference between applied water and drainage and adding to ET the stored water that was extracted by plant roots from the sand as measured with a neutron probe (Poss et al., 2004).

The experiment was a partial-factorial experimental design with no replication to evaluate the effects of salinity and water application on plant reflectance indices measured for the two field crops over a period of three cutting cycles. Of the 24 VLS units, half were used to grow alfalfa and half to grow tall wheatgrass (12 treatment combinations of irrigation water salinity and irrigation amounts orthogonally spaced over the desired ranges for each species, Table 1).

Irrigation volumes required to establish the four predetermined ETR targets were calculated independently for each species based on ratios of measured cumulative ET from their respective control: a high leaching fraction–low salinity treated plot (ET_0 = cumulative ET of Treatment 1, Table 1). The prescribed ETR volumes (ETR $\times$ ET_0) were then applied with the VLS by controlling the pump time that delivered a targeted volume of irrigation water to meet the water requirement based on the previous 2 d of accumulated ET. These volumes and pumping rates were previously calibrated with a water meter (Poss et al., 2004).

Table 1. Drought treatment ratios (ETR) and irrigation water salinity (electrical conductivity, EC) treatment targets and measured values of evapotranspiration (ET) and EC for alfalfa and tall wheatgrass. Irrigation volumes were applied as ratios of the ET measured from a very well watered control (Treatment 1). Measured ET is cumulative ET resulting from target ETR water applications and actual EC is the average of the irrigation and drainage water EC values (rootzone). Fresh biomass data presented was used for regression statistics in Table 4.

	Target		Alfalfa			Wheatgrass		
Treatment	ETR	EC	ET	EC	Yield	ET	EC	Yield
		dS m^{-1}	mm	dS m^{-1}	g plot^{-1}	mm	dS m^{-1}	g plot^{-1}
1	1.25 (control)	3	309	4.0	3622	294	3.2	2172
2	1.25	13	165	21.2	1538	214	22.1	1207
3	1.25	23	144	25.9	575	173	31.9	354
4	1	8	212	21.7	2027	229	17.4	848
5	1	18	160	25.9	889	175	25.7	716
6	1	28	94	34.0	148	133	38.8	282
7	0.75	3	270	3.8	2194	246	4.0	1399
8	0.75	13	160	25.5	846	193	27.4	599
9	0.75	23	142	50.3	339	142	39.6	359
10	0.5	8	185	9.1	860	167	16.3	426
11	0.5	18	149	24.4	264	158	29.4	299
12	0.5	28	98	36.3	116	105	42.2	143

The composition of the salinizing salts (Table 2) was intended to simulate drainage waters typically found in agricultural fields of the San Joaquin Valley of California where solution compositions are significantly higher in sulfate concentration than those found in many saline situations. Nutrients were initially added at N, P, and K levels similar to a half-Hoagland's nutrient solution. However, the exact compositions of the nutrient salts were adjusted to be consistent with respect to the major cation and anions in the simulated drainage water. To this control base (EC_{iw} treatment = 3 dS m^{-1}) additional salts were added to create the other five salinity treatments to maintain uniform nutrition.

After full canopy development, uniform salinity profiles were established with adequate irrigation. Water stress was imposed and the crops were grown for several months, thereafter, under combined salinity and drought treatments. The average air temperature, soil temperature at 10-cm depth, and atmospheric relative humidity during the course of the study were 25.6 ± 0.2, 24.0 ± 0.1, and 51.7 ± 0.6 during the day and 23.5 ± 0.7, 25.2 ± 0.2, and 50.8 ± 2.5 during the night, respectively. Incoming solar radiation measured with a Model 200x pyranometer (LI-COR, Lincoln, Nebraska), calibrated for daylight spectrum of 400 to 1000 nm, averaged 441 W m^{-2} with a maximum radiation reading of 954 W m^{-2}. The spectral data collected to develop the multiple linear regression model represented average reflectance of hyperspectral scans obtained during three separate remote measurement days (DOY 182, 189, and 192). These data were regressed against one harvest growth interval (fresh cutting to harvest) from 30 June 2003 (DOY = 181) through 11 July 2003 (DOY = 192) for wheatgrass and from 23 June 2003 (DOY 174) to 21 July 2003 (DOY 202) for alfalfa. During the entire study, simultaneous salinity and water stress was imposed on the crops. The electrical conductivities were monitored and the cumulative ET for each treatment was recorded (Table 1).

Canopy Reflectance Measurements

Reflectance of the forage canopy surface was measured at 350 to 1000 nm with a peak-to-peak bandwidth of about 1.5 nm with an ASD FieldSpec Pro spectroradiometer (Analytical Spectral Devices, Boulder, CO). During each measurement, three scans, each consisting of internal averages of 10 scans by the capturing software (RS^3; Analytical Spectral Devices), were obtained from each plot (81 cm wide × 202 cm long) under full canopy. The spectroradiometer was equipped with a fiberoptic cable configured with an 8° foreoptic accessory. A distance of 35 cm was maintained from the foreoptic to the canopy surface at nadir view (perpendicular to canopy surface) and at an obtuse 45° angle from the canopy surface for a spot size of approximately 5-cm diameter (19-cm^2 area for Nadir and 29-cm^2 area at 45°). Before each measurement, the instrument was optimized for integration time to allow for maximum allowable signal without saturation and calibrated to a white reference panel (99% Spectralon; Labsphere, North Sutton, NH) for percent reflectance through an automated optimization and white reflectance panel routine. Special attention was made to avoid shadows and minimize the effect of glare by positioning the foreoptic between the sun and the plot. Measurements were made as quickly as possible at similar times-of-day under full sun.

Statistical Design and Analysis

A quadratic surface response model was used for analysis of variance to test the level of significance that salinity and ETR treatments contributed to the fit of the experimental design response variables (y) expressed as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 + \varepsilon \quad [1]$$

where y represented fresh weight per plot or vegetative indices and variables x_1 and x_2 represent the actual measured average rootzone soil water salinity (dS m^{-1}) and cumulative ET (mm) for each ETR treatment, and ε is experimental error. This design allowed for statistical tests of main effects of salinity and water stress for each species without need for replication. The significance value or probability of obtaining at least as great an F ratio given that the null hypothesis is true was calculated for the particular variables as part of the regression analysis (RSREG procedure; SAS Institute, 1997) as was the significance of the contribution of each factor (cumulative ET and

Table 2. Composition of salinizing salts in solutions used to irrigate alfalfa and wheatgrass grown in outdoor lysimeters.

EC_i†	Ca^{2+}	Mg^{2+}	Na^{+}	SO_4^{2-}	Cl^{-}
dS m^{-1}	mol m^{-3}				
3.0	2.50	1.50	13.8	7.00	5.00
8.0	8.20	6.50	58.2	29.6	28.2
13.0	12.9	11.4	101	49.7	48.8
18.0	13.5	17.8	158	71.4	76.4
23.0	13.6	24.3	216	93.5	98.4
28.0	14.0	31.8	282	118	126

† Electrical conductivity.

average EC). Forage fresh weight was tested for significant variation due to salinity and cumulative ET with this quadratic regression model. Linear regressions of VIs and LAI and correlations of ground truths (fresh weight, electrical conductivity, evapotranspiration) with reflectances at specific wavelengths and spectra or VIs were performed with the GLM, REG, and CORR procedures, respectively (SAS Institute, 1997).

A green region NDVI [Onecartwr = $(R_{550nm} - R_{670nm})/(R_{550nm} + R_{670nm})$] and far red region NDVI [Twocartwr = $(R_{710nm} - R_{670nm})/(R_{710nm} + R_{670nm})$] were developed based on wavelength sensitivities reported by Carter (1993) where increased reflectance at both wavelengths (710 nm and 550 nm) were reported to respond to stress regardless of the stress agent or species measured. In both of these indices, the reference wavelength of 670 nm represented a sensitivity minimum that the wavelengths were subtracted from and then normalized. Another modified index developed in this article was a derivative-based red-edge position pseudo-absorbance (REPAsl) index modified from Rinehart et al. (2002). Instead of reporting the wavelength where the slope is the greatest [visible-red edge = log(1/R); Rinehart et al., 2002], our method reports the value of the steepest slope of the function in the region between 600 and 800 nm. Another VI, RFht, was an NDVI composed of the falling edge position height (reflectance value, FEPht) within 1250 to 1400 nm and the REPht within the 600 to 800 nm region. Two other hybrid NDVIs (NDVIcan, NDVIlf), whose components were NDVIs previously reported to be sensitive to pathogens (Steddom et al., 2003) and vegetation types (Tan et al., 2000), were also developed (see Table 3).

To compare our indices for salinity and water stress detection with a broad range of spectral indices cited for stress detection, 71 different vegetative indices were evaluated in this study (Table 3). Of these, 65 were calculated from the literature and the six mentioned above were developed based on inspection of treatment spectra or modifications of existing algorithms. The indices are organized into three basic types: ratios, normalized-difference vegetation indices, and derivative-based (Table 3). Several NDVIs sensitive to chlorophyll pigments (Barton, 2001; Read et al., 2002; Schepers et al., 1996; Steddom et al., 2003; Peñuelas and Inoue, 1999; Datt et al., 2003; Sims and Gamon, 2002) were tested as was one reported sensitive to LAI (Boegh et al., 2002). Simple ratios evaluated included one sensitive to LAI (Aparicio et al., 2002) and many reported to identify pigments (Steddom et al., 2003; Leblon et al., 2001; Carter et al., 1996; Read et al., 2002; Blackburn, 1998, 1999; Bausch and Diker, 2001; Luther and Carroll, 1999; Sims and Gamon, 2002; Jacobsen et al., 1998; Peñuelas et al., 1997, 1993), and one for salinity (Wang et al., 2002a, 2002b). Derivative-based indices were also calculated that are reportedly sensitive to pigments (Blackburn, 1998; Zarco-Tejada et al., 2002, 2003), LAI (Elvidge and Chen, 1995), and general stress (Rinehart et al., 2002). In each case, the reflectance was averaged over approximately 4.2 nm centered at the desired wavelength.

Temporal effects of differential canopy heights due to ETR and EC treatment effects were detected with remotely sensed indices by testing ET and EC effects at three different days from a period of time between a uniform cutting and harvest. Canopy reflectance was measured immediately after cutting wheatgrass on DOY 182 (uniform canopy height among treatments), on DOY 189, and just before the wheatgrass harvest (DOY 192). The alfalfa was also scanned on these same dates despite having a longer growth cycle between cutting and harvest.

A multiple linear regression model was also developed (GLM procedure; SAS Institute, 1997) to evaluate yield as a function of two remote sensing indices: an NDVI, Onecartwr, and an inverse of the Readthr (Read et al., 2002) index that was sensitive to N (Invreadthr). The yield data used to fit the model were from the DOY 192 harvest for wheatgrass and the DOY 202 harvest for alfalfa. The model used averages of the values of the two remote indices calculated from all three scanning events previously identified (DOY 182, 189, 192) to test cumulative ET and salinity effects over the course of canopy development. The three scan dates were averaged and regressed against the total fresh weight for each individual plot for each species ($n = 12$). To test the model developed for each species, the species-dependent coefficients developed from this harvest were applied to a prior harvest period (DOY 120 for wheatgrass and DOY 126 for alfalfa) and a later harvest period (DOY 212 for wheatgrass and DOY 226 for alfalfa).

RESULTS AND DISCUSSION

Water and Salinity Effects on Forage Yield

Both cumulative evapotranspiration and average root-zone electrical conductivity significantly influenced the yield of alfalfa and wheatgrass (Table 1). Increasing EC and decreasing cumulative ET both caused yield reductions of varying magnitude. For example, when alfalfa experienced a 40% reduction in water application (1.25ETR vs. 0.75ETR) yield decreased by 39% when salinity was 3 dS m^{-1}. When alfalfa was well irrigated (ETR = 1.25), and salinity increased from 3 to 13 dS m^{-1}, yield decreased by 58% (Table 1). The surface regression model was able to account for over 99% of the variation in yield imposed by both stressors. This is evidence that the model fits the data adequately, although partial replication would have allowed for a lack-of-fit test. The effects were primarily linear with a significant quadratic term accounting for less than 10% of the variation in the fresh weight (Table 4). The average biomass produced over the range of ETR and EC treatments was higher (1118 g fresh wt. per plot) for alfalfa than for wheatgrass (734 g fresh wt. per plot), despite a greater reported relative salt tolerance threshold and lower rate of growth reduction per unit increase reported for tall wheatgrass (Maas and Grattan, 1999).

Effect of Sensor Angle

For the DOY 212 data, effect of angle of the sensor relative to the canopy was evaluated based on the quadratic surface model (Eq. [1]) that assessed measured EC and ET effects on fresh weight. The angle had a large influence on the number of significant correlations between VIs as a function of measured EC and ET and this relationship differed between species. When the spectra were collected at a 45° angle from the nadir, 48 different vegetative indices were significantly changed by the salinity and ETR treatments for wheatgrass whereas from the nadir view only 22 of the indices were significantly correlated with both stressors ($P > F = 0.05$). For alfalfa, the effect was less pronounced with 22 indices varying significantly at 45°, and 16 significant from the nadir view angle ($P > F = 0.05$).

The effect of viewing angle was also evaluated by linear regression of each VI against leaf area index as estimated with a LI-COR Biosciences 2000 canopy analyzer. Alfalfa was more variable between sensor angles

Table 3. Vegetative indices (VI) evaluated in this study. The indices are divided into three types: ratio, NDVI, and derivative. Each VI has a name, a primary compound or factor that the VI is sensitive to, the credited author, and the formula.

VI	Type	Primary sensitivity	Author	Formula†
ARIlf	ratio	anthocyanin	Steddom et al. (2003)	(1/R550:R551) − (1/R700:R701)
Canbio	ratio	canopy biologicals	Leblon et al. (2001)	R667/R717
Fluocart	ratio	stress	Carter et al. (1996)	R690/R735
PSR	ratio	chlorophyll *a*	Read et al. (2002)	R430/R680
PSSRb	ratio	chlorophyll *b*	Blackburn (1998)	R800/R635
PSSRc	ratio	carotenoid	Blackburn (1998)	R800/R470
PSSRchla	ratio	chlorophyll *a* and *b*	Blackburn (1999)	R810/R676
PSSRchlb	ratio	carotenoid	Blackburn (1998)	R810/R682
quasiNRI	ratio	nitrogen (N)	Bausch and Duke (1996)	(R780:R850)/(R530:R570)
Ratlut	ratio	treatment effects	Luther and Carroll (1999)	R711/R913
Ratcart	ratio	chlorophyll	Carter et al. (1996)	R695/R760
Readone	ratio	chlorophyll	Read et al. (2002)	R415/R695
Readthr‡	ratio	N	Read et al. (2002)	R415/R710
Readtwo	ratio	carotenoids	Read et al. (2002)	R415/R685
RVI	ratio	N and seed yield	Jacobsen et al. (1998)	(R790:R810)/(R640:R660)
SR680	ratio	chlorophyll	Sims and Gamon (2002)	R800/R680
SR705	ratio	chlorophyll	Sims and Gamon (2002)	R750/R705
Srapa	ratio	LAI	Aparicio et al. (2002)	R900/R680
SRVI	ratio	salt stress	Wang et al. (2002a, 2002b)	R830/R660
Wipen	ratio	plant water status	Peñuelas et al. (1997)	R970/R900
Wnratpen	ratio	plant water status	Peñuelas et al. (1997)	Wipen/NDVIbpen
BROboe	NDVI	LAI (green)	Boegh et al. (2002)	(R748 + R778 − R550 − R620 − R671)/(R748 + R778 + R550 + R620 + R671)
CHLboe	NDVI	chlorophyll	Boegh et al. (2002)	(R748 + R778 − R550)/(R748 + R778 + R550)
CRIlf	NDVI	carotenoid	Steddom et al. (2003)	(1/R505:R515) − (1/R535:R565)
EVIboe	NDVI	LAI (freen)	Boegh et al. (2002)	(2.5(R748 + R778) − R670)/(1 + R748 + R778 + 6 R670 − 7.5 R457)
LAIboe	NDVI	LAI	Boegh et al. (2002)	(R748 + R778 − R670)/(R748 + R778 + R670)
LCIIdatt	NDVI	chlorophyll	Datt et al. (2003)	(R850 − R710)/(R850 − R680)
MND705	NDVI	chlorophyll	Sims and Gamon (2002)	(R750 − R705)/(R750 + R705 − 2(R445))
MSR705	NDVI	chlorophyll	Sims and Gamon (2002)	(R750 − R445)/(R705 − R445)
ND705	NDVI	chlorophyll	Sims and Gamon (2002)	(R750 − R705)/(R750 + R705)
NDVIapen	NDVI	WIPEN correction	Peñuelas et al. (1997)	(R900 − R680)/(R900 + R680)
NDVIbpen	NDVI	used for correcting WIPEN	Peñuelas et al. (1997)	(R800 − R680)/(R800 + R680)
NDVIcan‡	NDVI	chlorophyll	this paper	(NDVIcanste − NDVIcantan)/(NDVIcanste + NDVIcantan)
NDVIcanste	NDVI	chlorophyll	Steddom et al. (2003)	(R760 − R708)/(R760 + R708)
NDVIcantan	NDVI	chlorophyll	Tan et al. (2000)	(R673 − R890)/(R673 + R890)
NDVIlf‡	NDVI	chlorophyll	this paper	(NDVIlfste − NDVIlftan)/(NDVIlfste + NDVIlftan)
NDVIlfste	NDVI	chlorophyll	Steddom et al. (2003)	[(R745:R755) − (R700:R710)]/[(R745:R755) + (R700:R710)]
NDVIlftan	NDVI	chlorophyll	Tan et al. (2000)	(R673 − R759)/(R673 + R759)
NDVIlut	NDVI	treatment effects	Luther and Carroll (1999)	(R913 − R711)/(R913 + R711)
LCIIdatt	NDVI	water content	Datt et al. (2003)	(R860 − R1240)/(R860 + R1240)
NPCI	NDVI	carotenoid/chlorophyll *a*	Read et al. (2002)	(R680 − R430)/(R680 + R430)
Onecartwr‡	NDVI	stress	this paper	(R550 − R670)/(R550 + R670)
Onesch	NDVI	chlorophyll	Schepers et al. (1996)	R550/R850
PRImet	NDVI	photsyn. rad. use eff.	Méthy et al. (1999)	(R531 − R570)/(R531 + R570)
PSNDb	NDVI	chlorophyll *b*	Blackburn (1998)	(R800 − R635)/(R800 + R635)
PSNDc	NDVI	carotenoid	Blackburn (1998)	(R800 − R470)/(R800 + R470)
PSRI	NDVI	chlorophyll	Sims and Gamon (2002)	(R680 − R500)/R750
REPht	NDVI	stress	Barton (2001)	REIP height within 600:800
REPref	NDVI	stress	Barton (2001)	REIP within 600:800
RFht‡	NDVI	stress	this paper	(REPht − FEPht)/(REPht + FEPht) (FEPht within 1200–1450 nm)
RGRcan	NDVI	anthocyanin/chlorophyll	Steddom et al. (2003)	(R612 + R660)/(R510 + R560)
RGRlf	NDVI	anthocyanin/chlorophyll	Steddom et al. (2003)	(R600:R699)/(R500:R599)
SIPIpen	NDVI	carotenoids/chlorophyll	Peñuelas and Inoue (1999)	(R800 − R445)/(R800 + R445)
Twocartwr‡	NDVI	stress	this paper	(R710 − R670)/(R710 + R670)
Twosch	NDVI	photosyn. activity/chlorophyll	Schepers et al. (1996)	R710/R850
VARIcan	NDVI	canopy coverage	Steddom et al. (2003)	(R560 − R660)/(R560 + R660 − R459)
Blackder453	derivative	carotenoid	Blackburn (1998)	D453
Blackder726	derivative	carotenoid	Blackburn (1998)	DD726
Blackder664	derivative	chlorophyll *a* and *b*	Blackburn (1998)	DD664
Blackder730	derivative	chlorophyll *a* and *b*	Blackburn (1998)	D730
Blackder732	derivative	chlorophyll *b*	Blackburn (1998)	D732
DCI	derivative	chlorophyl fluor.	Zarco-Tejada et al. (2002)	D705/D722
DPI	derivative	chlorophyl fluor.	Zarco-Tejada et al. (2002)	(D688 × D710)/Sqrt[D697]
DPIarea	derivative	chlorophyl fluor.	Zarco-Tejada et al. (2003)	area under DPI curve
Blackder717	derivative	carotenoid	Blackburn (1998)	D717
D1B	derivative	LAI	Elvidge and Chen (1995)	integrated over 626:795
D2Z	derivative	LAI	Elvidge and Chen (1995)	integrated over 626:795
REPabs	derivative	stress	Rinehart et al. (2002)	REIP within 600:800
REPAsl‡	derivative	stress	this paper	REIP slope within 600:800

† Reflectance = R, red-edge position = REP (sl = slope), red-edge inflection point = REIP, falling edge position = FEP, derivative = D, second derivative = DD, crop canopy reflectance = suffix "can", plant leaf reflectance = suffix "lf", height/reflectance value = suffix "ht".
‡ Final VIs chosen for analysis.

Table 4. Surface model statistics for total fresh weight (g), and two vegetative indices (VIs) for wheatgrass and alfalfa regressed against average irrigation water electrical conductivity (EC, dS m^{-1}) and cumulative evapotranspiration (ET, mm); n = 12.

Forage	Factor/VI	Regression	df	r^2	F value	$P > F$	Mean	CV
								%
Alfalfa	Fresh	linear	2	0.9478	621	<0.0001	1118	8.62
	Biomass	quadratic	2	0.0471	30.9	0.0007		
		crossproduct	1	0.0005	0.62	0.4617		
		total model	5	0.9954	261	<0.0001		
	EC	factor	3		4.83	0.0485		
	ET	analysis	3		119	<0.0001		
		linear	2	0.7049	8.78	0.0165	0.2081	11.4
	Readthr	quadratic	2	0.0318	0.40	0.6895		
		crossproduct	1	0.0225	0.56	0.4827		
		total model	5	0.7592	3.78	0.0681		
	EC	factor	3		0.60	0.6389		
	ET	analysis	3		1.41	0.3284		
	Onecartwr	linear	2	0.8661	117	<0.0001	0.1954	18.2
		quadratic	2	0.0929	12.6	0.0072		
		crossproduct	1	0.0188	5.07	0.0654		
		total model	5	0.9778	52.8	<0.0001		
	EC	factor	3		8.05	0.0159		
	ET	analysis	3		31.8	0.0004		
Wheatgrass	Fresh	linear	2	0.9218	367	<0.0001	733.7	9.52
	Biomass	quadratic	2	0.0672	26.8	0.001		
		crossproduct	1	0.0035	2.76	0.1479		
		total model	5	0.9925	158	<0.0001		
	EC	factor	3		4.17	0.0649		
	ET	analysis	3		105	<0.0001		
		linear	2	0.0631	0.30	0.749	0.2169	20.7
	Readthr	quadratic	2	0.3125	1.50	0.296		
		crossproduct	1	0.0001	0	0.981		
		total model	5	0.3757	0.72	0.6309		
	EC	factor	3		1.02	0.4463		
	ET	analysis	3		0.55	0.6687		
	Onecartwr	linear	2	0.7603	14.0	0.0055	−0.0620	−80.9
		quadratic	2	0.0161	0.30	0.7529		
		crossproduct	1	0.0610	2.25	0.1843		
		total model	5	0.8374	6.18	0.0232		
	EC	factor	3		0.91	0.0712		
	ET	analysis	3		3.97	0.4903		

in terms of the correlation between indices and leaf area index, but for both crops the 45° sensor angle gave better correlations for the VIs tested (Table 5). The reason for greater correlations may be associated with the influence of soil on the reflectance measurements. Similar improvements in VI sensitivities were noted by Bausch and Diker (2001) in corn canopies where they found oblique views at 75° from nadir more sensitive to N when soil background was minimized either by angle or canopy development beyond the V12 growth stage. Another explanation may be due to the size of the area of measurement (assuming a relatively flat canopy surface). At the same distance from the canopy, the oblique angle spot area (45° degree angle) is greater by 50%. This may result in a more representative spatial average of canopy reflectance producing better correlations when compared with smaller spot areas. Based on this analysis, the spectra presented for this study were exclusively obtained from the 45° viewing angle.

Water and Salinity Effects on Canopy Reflectance

Salinity and water stress reduced the NIR reflectance (from 760 to 1000 nm) from the canopy as the magnitude of the stress increased for both crops (Fig. 1). When the total combination of salinity and ETR treatments was averaged across low salinity ($EC_{iw} \leq 8$ dS m^{-1}), the reflectance was slightly greater than when averaged across high salinity treatments (EC > 8 dS m^{-1}, Fig. 1a) for wheatgrass. Salinity stress had a more dramatic reduction in the NIR for alfalfa (Fig. 1b). The effect of water stress on canopy reflectance was found to reduce reflectance from the canopy in the NIR as demonstrated by averaging across high water stressed (ETR < 1.0, low ET) and low water stressed treatments (ETR ≥ 1.0, high ET). Water stress had a greater effect on reflectance than did salinity for the particular treatments imposed in this study, although for alfalfa the effects of both stressors had more similar effects than for wheatgrass (Fig. 1a and 1b). The effect of water and salinity stress was greatest on plant reflectance for alfalfa (Fig. 1b) when compared with wheatgrass, where absolute values and differences in reflectance were less (Fig. 1a). Canopy reflectance in the visible domain (Fig. 2) was increased with salinity for wheatgrass, but for alfalfa the reflectance of non-saline plants increased above that of saline alfalfa (Fig. 2b) in the "green peak" region (550 nm). This phenomenon could be attributed to either (i) development of N deficiency in the faster growing non-saline treatments, causing an increase in canopy reflectance; or (ii) possible N excess in salt stressed plants, causing a decrease in reflectance due to the very high N content of alfalfa at high salinities (Fig. 3).

The coefficients of determination (r^2) for the linear relationships between canopy reflectance (at individual wavebands centered from 350 to 1000 nm, collected on DOY 212) and forage fresh weights, measured cumulative evapotranspiration, and irrigation water electrical

Table 5. Effect of sensor angle on the correlation between vegetative indices listed in Table 3 and leaf area index (LAI). Vegetative indices (VIs) were calculated from reflectance measurements at 45° from nadir and nadir (90°) sensor angles. Correlations listed were greater than 0.3 ($P > F = 0.05$) with leaf area index. Correlations are higher in nearly all cases at 45° from nadir.

	Alfalfa		Wheatgrass	
	Sensor angle			
VI	45°	90°	45°	90°
Fluocart	<0.30	<0.30	0.74	0.58
PSR	0.55	0.54	0.76	0.55
PSSRb	0.93	0.72	0.71	0.49
PSSRc	0.9	0.77	0.59	0.46
PSSRchla	0.94	0.77	0.72	0.47
PSSRchlb	0.94	0.77	0.72	0.47
quasiNRI	0.78	0.43	<0.30	<0.30
Readone	<0.30	<0.30	0.62	0.5
Readthr	0.72	0.62	<0.30	<0.30
Readtwo	0.57	0.54	0.74	0.56
RVI	0.95	0.72	0.7	0.49
Srapa	0.94	0.77	0.73	0.48
SRVI	0.95	0.77	0.72	0.48
Wipen	0.74	0.36	0.55	0.5
Wnratpen	<0.30	<0.30	0.61	0.52
ARIlf	<0.30	<0.30	0.61	0.52
BROboe	0.79	0.38	0.68	0.55
CRIlf	0.69	0.68	<0.30	<0.30
EVIboe	0.57	0.49	<0.30	<0.30
LAIboe	0.81	0.38	0.75	0.57
MND705	<0.30	<0.30	0.66	0.53
MSR705	<0.30	<0.30	0.69	0.49
ND705	<0.30	<0.30	0.68	0.54
NDVIapen	0.8	0.4	0.73	0.57
NDVIbpen	0.81	0.37	0.74	<0.30
NDVIcan	<0.30	<0.30	0.57	<0.30
NDVIcantan	0.81	0.41	0.73	0.57
NDVIlfste	<0.30	<0.30	0.68	0.54
NDVIlftan	0.82	0.38	0.75	0.57
NPCI	0.55	0.42	0.77	0.57
Onecartwr	0.92	0.65	0.86	0.59
PRImet	0.72	0.49	0.8	0.57
PSNDb	0.78	0.4	0.7	0.56
PSNDc	0.79	0.59	<0.30	<0.30
PSRI	<0.30	<0.30	0.72	0.58
REPht	0.57	0.51	<0.30	<0.30
RGRcan	0.86	0.52	0.82	0.61
RGRlf	0.85	0.51	0.83	0.62
SIPIpen	<0.30	<0.30	0.65	0.49
SR680	0.68	0.33	0.68	0.48
SR705	0.71	0.38	0.7	0.5
Twocartwr	0.92	0.67	0.86	0.56
Twosch	<0.30	<0.30	0.55	0.5
VARIcan	0.88	0.65	0.85	0.58
Blackder453	<0.30	0.47	0.62	0.49
Blackder717	0.65	<0.30	0.7	0.59
D1B	0.53	0.52	<0.30	<0.30
REPabs	0.56	0.41	0.65	0.46
REPAsl	0.94	0.73	0.84	0.56

conductivity for wheatgrass (28-d growth period) and alfalfa (20-d growth period) were calculated (Fig. 4).

Overall, the correlations were slightly higher for these variables with alfalfa over wheatgrass. For alfalfa, a high correlation was observed at wavelengths around 710 nm, but there was little correlation with electrical conductivity for wheatgrass (Fig. 4e) in this region. The region of low sensitivity near 670 nm had very high correlations with fresh weight (Fig. 2a and 2b) ET and EC with the exception being EC for alfalfa (Fig. 4f.). A similar correlation structure was evident for wheatgrass and alfalfa when related to cumulative ET (Fig. 4c and 4d, respectively). The crops differed, however, with respect to average EC of the applied irrigation water; alfalfa was better correlated with reflectance in the green peak region (550 nm, Fig. 4f) than was wheatgrass (550 nm, Fig. 4e).

Water and Salinity Effects on Vegetative Indices

The effect of canopy height development on the ability to remotely sense salinity and water stress was evaluated with canopy spectra collected during three separate days (DOY 182, 189, 192) before the middle harvest. Three VIs developed in this study (Onecartwr, Twocartwr, and REPAsl) were calculated and regressed as a function of measured EC and ET with the surface regression analysis (Eq. [1]) for each date and crop (Table 6). Water stress (ET) was significant ($P < 0.05$) for all three VIs for both crops on DOY 182 and DOY 192, but not DOY 189 (except for Onecartwr on DOY 182 that was also not significantly influenced by ET, Table 6). For EC, only the two indices sensitive to the NIR, REPAsl and Twocartwr, were influenced by salinity in wheatgrass on DOY 192 whereas none were significant for alfalfa on any date. The DOY 182 spectra were taken immediately after the wheatgrass crop was cut, therefore all treatment wheatgrass canopy heights were the same and alfalfa was similar due to minimal re-growth. Nevertheless, plant cover differences were apparent for ETR treatments for alfalfa and wheatgrass with one exception (Onecartwr on DOY 182). The last scan (DOY 192) was just before the wheatgrass harvest when canopy height and development differences were substantial across the salt and water-stressed

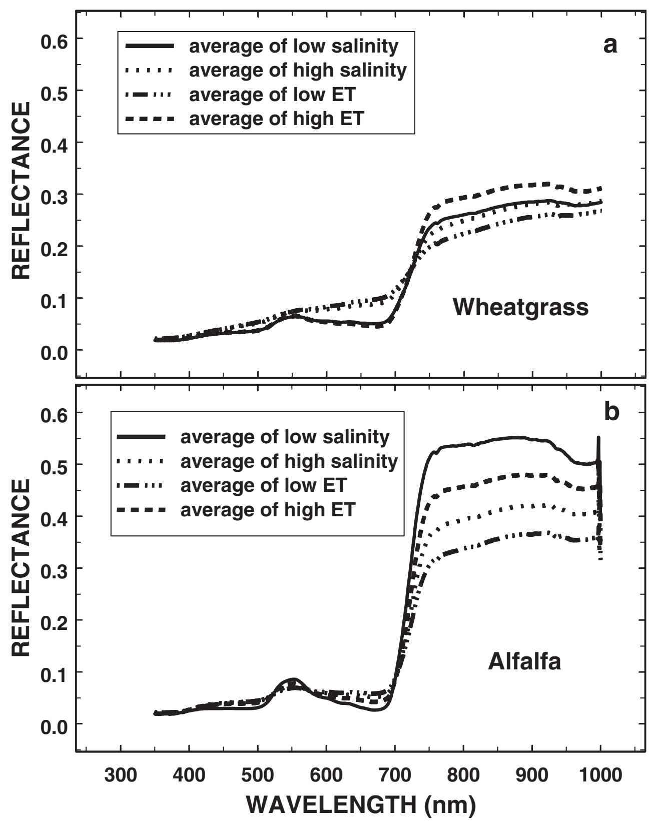

Fig. 1. Spectra obtained from 350 to 1000 nm averaging canopy reflectance over high and low salinity and evapotranspiration (ET) treatments for (a) wheatgrass and (b) alfalfa. Both salinity and drought reduced reflectance in the near-infrared (NIR) region.

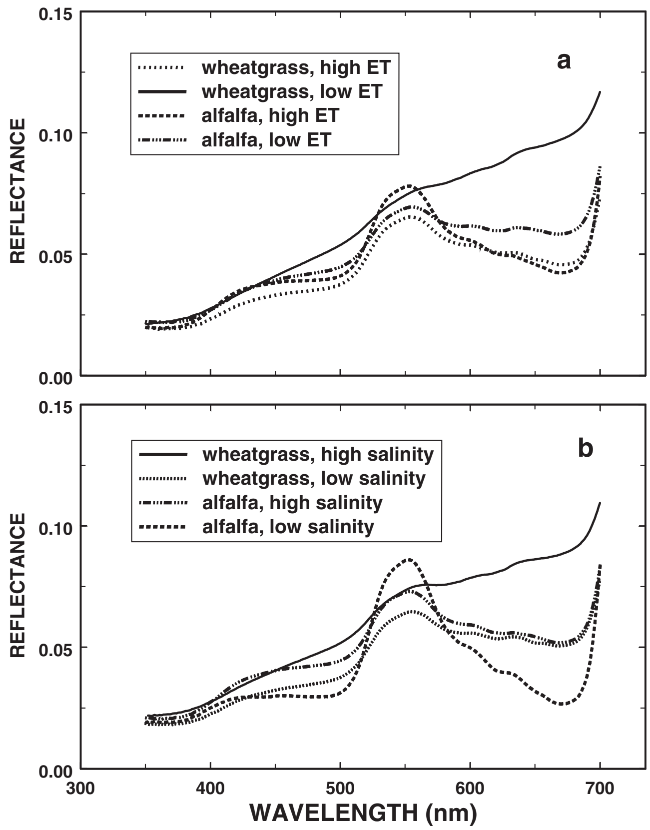

Fig. 2. Spectra obtained from 350 to 700 nm averaging canopy reflectance for wheatgrass and alfalfa for (a) high and low evapotranspiration (ET) and (b) over high and low salinity. Both salinity and drought increased reflectance in the visible region except for alfalfa where nitrogen concentrations confounded the "green peak" (550 nm).

treatments. In contrast to DOY 182, after substantial canopy development (DOY 192) most indices were significantly influenced by changes in cumulative ET for both species, but EC effects were only detected for two VIs (REPAsl and Twocartwr) for wheatgrass only (Table 6).

Estimating Yields with Multiple Linear Regression

The two factors that influence VIs in this study appeared to be related best to LAI and nitrogen/pigments for alfalfa only. Onecartwr was chosen based on the greatest correlation to LAI of the 71 VIs evaluated for wheatgrass and close to the highest for alfalfa (Table 5). The N sensitive Readthr index was assumed to be related to N contents in this study.

The middle harvest growth period included 22 d of re-growth for wheatgrass (Fig. 5a) and 28 d of re-growth for alfalfa (Fig. 5b). The model was better able to fit total fresh weight data to the remote indices for alfalfa (r^2 = 0.94) than for wheatgrass (r^2 = 0.72), but was significant for both crops.

The coefficients estimated for these two crops (Table 7) were then applied to the linear model with the two remote indices, Onecartwr and Invreadthr, as input and the resulting equation used to predict the total fresh weight biomass for each crop. Reflectance measurements from

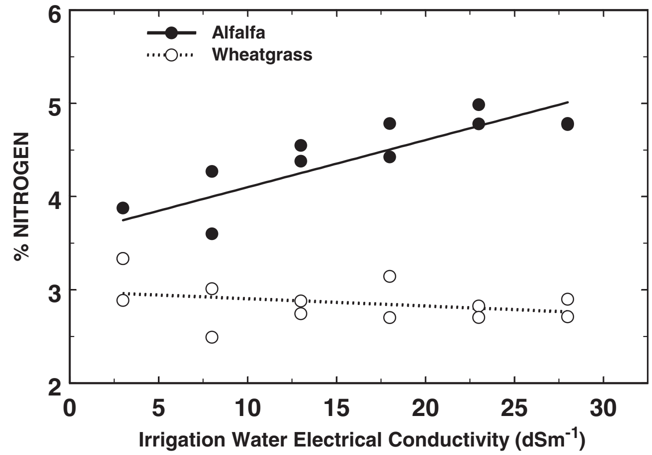

Fig. 3. A significant increase in tissue nitrogen with salinity was found for alfalfa but not wheatgrass. The effect of water stress on N content was not significant for either species (data not shown).

the prior cutting period and from the post model-development harvest were used to estimate yields for the respective periods. For the prior harvest [(DOY 120 for wheatgrass (Fig. 6a) and DOY 126 for alfalfa (Fig. 6b)], the relationship between the predicted and actual fresh weights was significant for both alfalfa (r^2 = 0.64) and wheatgrass (r^2 = 0.31). For the post harvest period [DOY 212 for wheatgrass and DOY 226 for alfalfa (Fig. 6c and 6d)], a very good relation was found for wheatgrass (r^2 = 0.95), and a nearly significant relationship ($P < 0.09$) for alfalfa (r^2 = 0.23) on DOY 226. Those points that deviated from the regression line significantly were plots with lower than average LAI.

The angle of the sensor had an effect on the relationship between remote indices and leaf area index. From the nadir view, more of the soil influence was registered, whereas at a more obtuse angle (in this study 45°) a greater number of correlations were found, perhaps indicating a greater influence of vegetation relative to soil reflectance at this angle.

Salinity and water stress had similar effects on crop canopy reflectance for both alfalfa and wheatgrass. As combined salinity and water stress increased, canopy reflectance decreased in the NIR. This change in reflectance was most notable in the slope of the red edge region and the absolute reflectance above 700 nm. These findings are consistent with those of Wang et al. (2002a, 2002b) who also reported a decrease in reflectance in the NIR domain. Furthermore, the relative decrease in canopy reflectance associated with stress was of greater magnitude for alfalfa than for wheatgrass in this region. This is consistent with the overall salt tolerance classification for the two crops, with a reported threshold of 2.0 dS m^{-1} for alfalfa and 7.5 dS m^{-1} for wheatgrass (Maas and Grattan, 1999). That water stress and salinity had a similar influence on the variation in yield and remote sensing indices for both crops may be an indication of plant response to total water potential and plant reflectance manifestations related to this difference in water potential among treatments. In the sand tank VLS, there was a very narrow range of moisture retention and

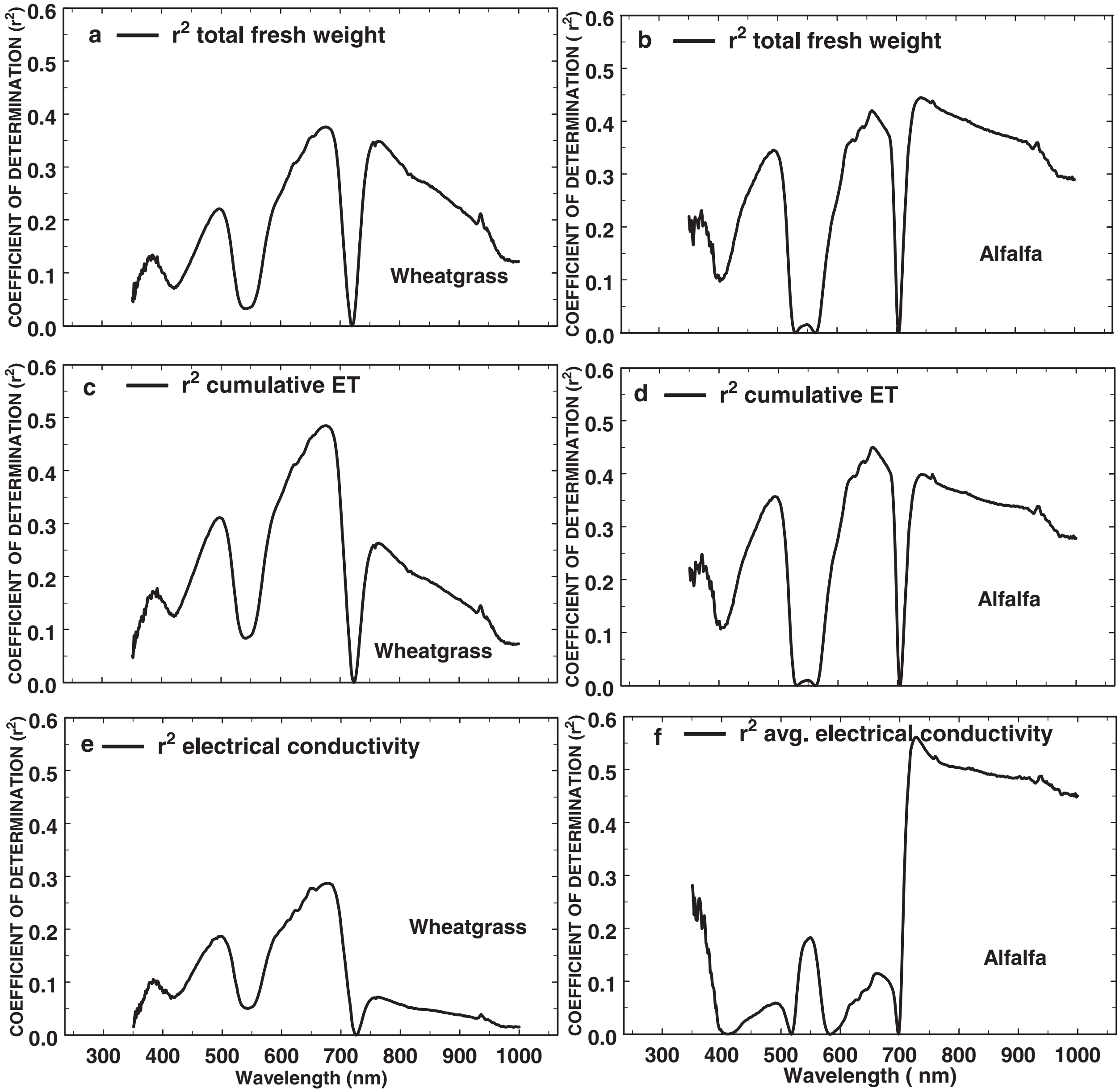

Fig. 4. Coefficients of determination (r^2) for the linear relationships between canopy reflectance at each wavelength and total fresh weight biomass for (a) wheatgrass and (b) alfalfa, total cumulative evapotranspiration for (c) wheatgrass and (d) alfalfa, and the integrated electrical conductivity of the irrigation water for (e) wheatgrass and (f) alfalfa.

volumetric water contents (θ_v) below 5% that would be expected to decrease the matric potential dramatically when compared to the minimum −0.1 MPa that would be expected in a soil well irrigated with 28 dS m^{-1} quality water [assuming osmotic potential = −0.36 × EC (dS m^{-1})]. This may account for greater probabilities of significant differences attributed to drought treatments over salinity.

The index, Onecartwr, based on visible wavelengths was found to be useful, contrary to Wang et al. (2002b) who found no relationship, for estimating yields under salinity and water stress. This may have been due to the lack of resolution in the nine-channel spectrometer used in their study, which was unable to distinguish small changes in the green peak region. The effect of available N and related changes in pigmentation development (chlorophyll dominated) also appear to be another source of error in the relationship between salinity stress and forage canopy reflectance in soybean and elephant grass (Wang et al., 2002a, 2002b).

Leaf N was lowest for two treatments: upper left of Fig. 6a and 6b at the earlier harvest (DOY 120 and 126) for wheatgrass and alfalfa, respectively. Alfalfa N in this plot was 2.7% vs. 4.0% averaged over the other eleven plots. For wheatgrass the outlier point N was 2.1% vs. 3.2% averaged over the other eleven plots. Interestingly, for each crop this anomaly was observed in the 0.5 ETR, 8 dS m^{-1} EC treatment and there was a significant effect of N on yield of both crops on these early cuttings. That N was lower for these plots may explain why increased

Table 6. Probability of a greater *F*, coefficient of determination, and surface means for three vegetative indices regressed against average irrigation water electrical conductivity (EC) and cumulative evapotranspiration (ET). Analysis was for two crops, wheatgrass and alfalfa, remotely measured on three successive dates from recently harvested stubble (DOY 182) to before harvest (DOY 192).

		Wheatgrass				Alfalfa			
VI	DOY	EC	ET	r^2	Mean	EC	ET	r^2	Mean
REPAsl	182	0.192	0.038	0.84	−0.022	0.192	0.041	0.80	−0.017
Onecartwr		0.244	0.164	0.76	−0.071	0.191	0.044	0.80	1.10
Twocartwr		0.618	0.049	0.79	0.495	0.212	0.024	0.81	0.158
REPAsl	189	0.445	0.155	0.74	−0.026	0.689	0.109	0.90	0.054
Onecartwr		0.427	0.101	0.86	−0.038	0.322	0.065	0.93	0.233
Twocartwr		0.321	0.16	0.8	0.241	0.719	0.104	0.91	0.497
REPAsl	192	0.002	0.001	0.98	−0.038	0.182	0.007	0.96	−0.061
Onecartwr		0.211	0.003	0.95	0.093	0.288	0.009	0.95	0.287
Twocartwr		0.007	0.001	0.98	0.364	0.243	0.009	0.96	0.542

visible reflectance due to N deficiency (Carter, 1993) caused a prediction of higher yield with indices responsive to water and salt stress. Addition of a term to adjust for tissue N concentration, the inverse of the nitrogen sensitive index, Readthr, developed by Read et al. (2002), improved the capability of the model to predict yield over a model with the NDVI Onecartwr as the only parameter. The effect of adding the Invreadthr term generated greater corrections for alfalfa than for wheatgrass. This can be attributed to the lack of a significant relationship between reflectance and the Invreadthr parameter ($P < 0.155$, Table 7) for wheatgrass that was observed in the

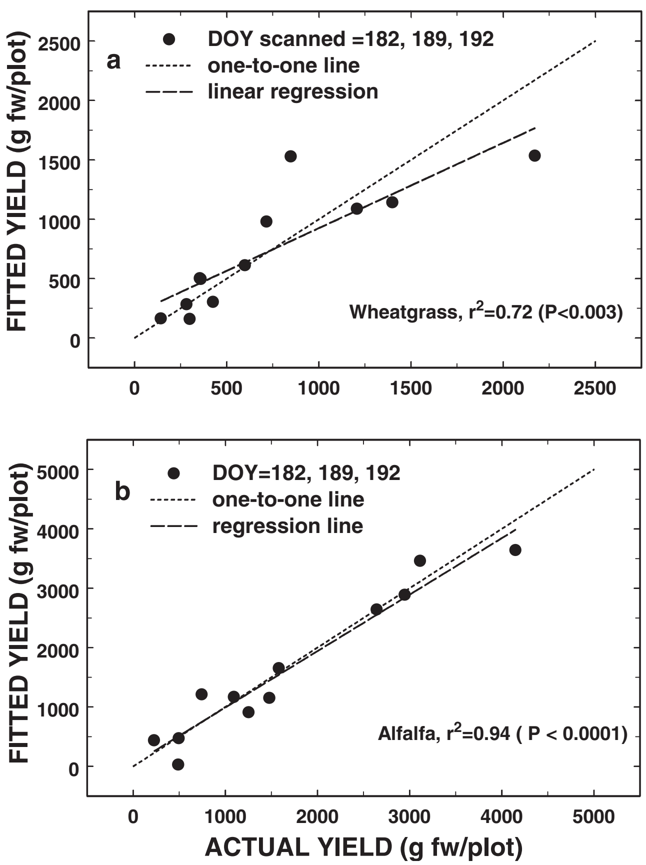

Fig. 5. The fitted estimate of yield and the coefficient of determination of a multiple linear regression model composed of two vegetative indices, Onecartwr and the inverse of Readthr. Coefficients provided from this fit were applied to predict yield of other harvests under similar environmental conditions.

analysis of the second harvest data that was used to estimate the model parameter coefficients. Error due to N nutrition may be related to the lack of prediction capability for alfalfa on scans obtained on DOY 226 where a greater degree of variation in N content was found in alfalfa during this period than was found for wheatgrass (Fig. 3). The relationship between yield and percent N in the tissue was significant for alfalfa but not for wheatgrass ($P > F = 0.002$ for alfalfa vs. $P > F$ 0.80 for wheatgrass), indicating that alfalfa yield was indeed affected by N content. Once again, an increase in the visible reflectance value may potentially explain this overestimation of yield for alfalfa by the model under these conditions. For wheatgrass, a much better relationship was found when no significant effect of N was observed. In research on plant stress, Carter (1993) and Carter and Young (1993) described nitrogen and flooding stress in barrier islands in the Gulf of Mexico. These stresses are associated with a chlorosis related to N deficiency that is manifest through increased visible reflectance in plant tissue with loss of N and chlorophyll development.

Leaf area index values below a minimum threshold also appear to be a source of error when relating VIs and yield under salinity and water stress. When the treatments with the lowest leaf area index values were omitted from the regression, the predictive capability of the model increased in each case. For the regression of wheatgrass on DOY 120, the coefficient of determination would have increased from 0.31 to 0.67 (Fig. 6a); for wheatgrass on DOY 212 the increase was from 0.95 to 0.97 (Fig. 6c); for alfalfa on DOY 126 the increase was from 0.64 to 0.76 (Fig. 6b); for alfalfa on DOY 226 the increase was from 0.23 to 0.66 (Fig. 6d). This may be related to a reduction in reflectance in the NIR related to soil exposure that is not associated with any change in leaf reflectance (Colwell, 1974).

CONCLUSIONS

The ability of narrow-band remote sensing of canopy reflectance to detect the effects of salinity and water stress was determined for alfalfa and wheatgrass forage crops. Three indices presented, Onecartwr, Twocartwr, and REPAsl, provided improved correlations over similar indices reported in the literature for both species (Table 5). These differences are primarily attributed to finer resolution data and subtle differences in the way

Table 7. Multiple linear regression parameter estimates and related statistics for harvest data used for model development. These coefficients were applied to the model for two separate harvest periods before and after this harvest ($n = 12$ for each period) to evaluate the model ability to estimate forage yield with remotely sensed indices Onecartwr and Invreadthr.

Forage	Parameter	Estimate	SE	t Value	$P > \|t\|$	r^2
	intercept	19.34	679.1	0.03	0.979	0.72
Wheatgrass	Onecartwr	5075	1156	4.39	0.002	
	Invreadthr	216.5	139.6	1.55	0.155	
	intercept	−1822	945.3	−1.93	0.066	0.94
Alfalfa	Onecartwr	4785	1005	4.76	0.001	
	Invreadthr	512.0	216.6	2.36	0.042	

the indices are calculated (e.g., differences in wavelength, bandwidth, derivative techniques). These indices warrant further testing for their ability to characterize salinity and water stress. That these improved indices were developed with narrowband remote sensing coupled with accurate ground-truthing indicates future potential to discriminate between factors that influence crop canopy reflectance.

A multiple linear regression model was developed that related alfalfa and wheatgrass yields with remote indices; Onecartwr that used the green (550 nm) and red (670 nm) region, and Invreadthr that used the violet-blue (415 nm) and the NIR (710 nm) regions. Despite significant predictive capabilities of remote sensing under similar growth conditions for both crops, the effect of N nutrition and bare soil exposure on canopy reflectance may have confounded the effects observed due to salt and water stress. More research on the ability to discriminate between drought, salt, and nutrient stress and canopy development with remote sensing of cropped fields is needed based on studies where variables that influence plant canopy reflectance can be closely monitored and controlled. Remote sensing models can then be developed that will predict yield under salinity and water stress by correcting for changes in plant reflectance, and hence yields, due to variations in plant nutrition and soil reflectance properties.

ACKNOWLEDGMENTS

The authors thank Dr. Paul J. Pinter, Jr. with the USDA-ARS U.S. Water Conservation Laboratory for his careful review of the manuscript. The advice and cooperation of Dr. Peter J. Shouse in establishing the drought treatments and quantifying evapotrans-

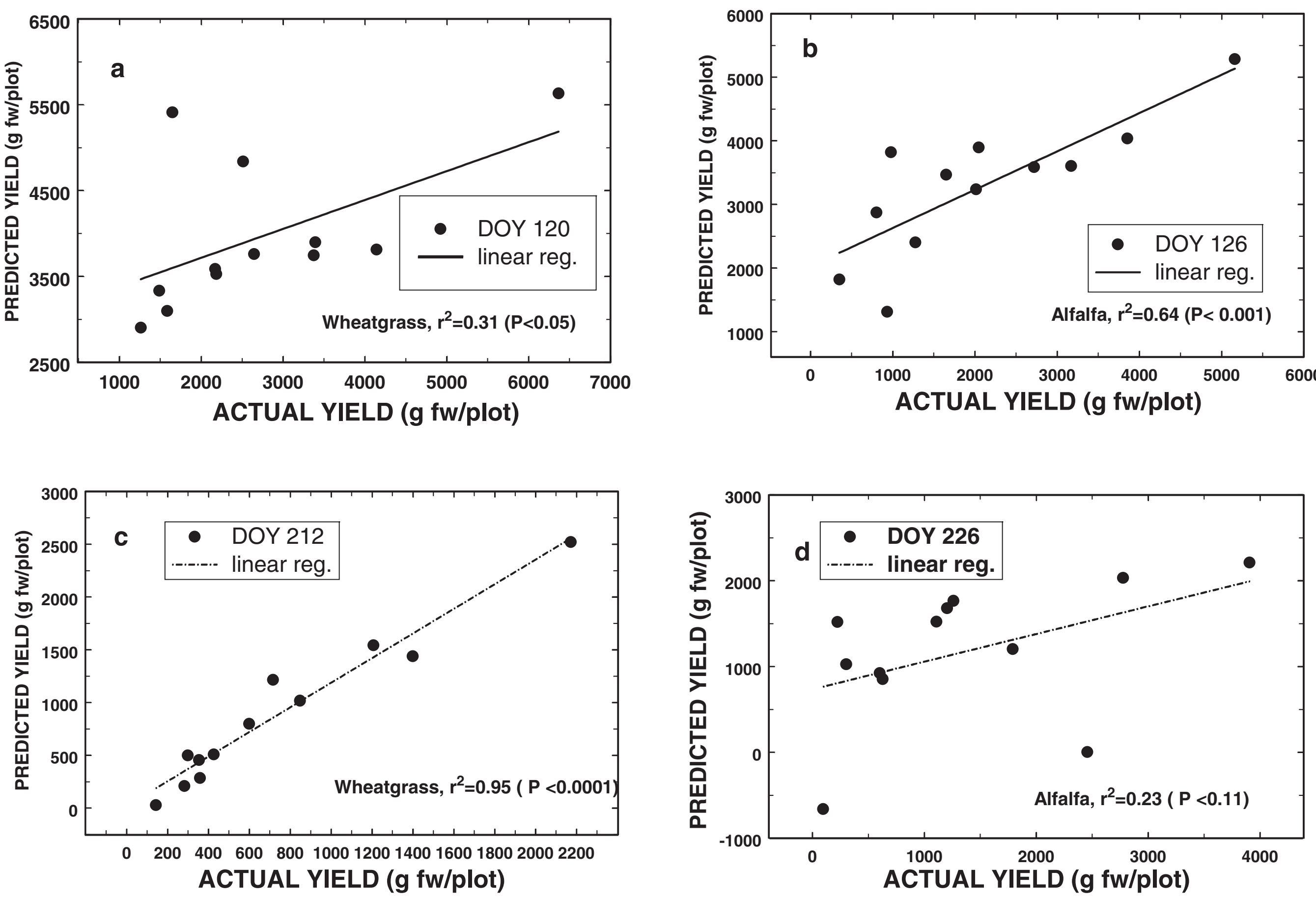

Fig. 6. The results of predicting yield from a multiple linear regression model when applied to forage production under simultaneous water and salinity stress for wheatgrass and alfalfa on a "prior" harvest period (a and b) and a "post" harvest period (c and d) with species-dependent coefficients.

piration is greatly appreciated. We thank Mr. Scott Lesch, Principal Statistician, for his statistical review. We want to thank Mr. Jack Jobes for monitoring soil moisture content with the neutron probe, and Mrs. JoAn Fargerlund and Mr. John Draper for their assistance with the nitrogen analysis. Also thanks to Mr. Doug Diaz and Ms. Kathy Kim who managed the experiment, acquired hyperspectral scans and LAI canopy analysis, quantified the harvest, and prepared plant tissues for analysis.

REFERENCES

Aparicio, N., D. Villegas, J. Al Araus, J. Casadesús, and C. Royo. 2002. Relationship between growth traits and spectral vegetation indices in durum wheat. Crop Sci. 42:1547–1555.

Barton, C.V.M. 2001. A theoretical analysis of the influence of heterogeneity in chlorophyll distribution on leaf reflectance. Tree Physiol. 21:789–795.

Bausch, W.C., and K. Diker. 2001. Innovative remote sensing techniques to increase nitrogen use efficiency of corn. Commun. Soil Sci. Plant Anal. 32:1371–1390.

Bausch, W.C., and H.R. Duke. 1996. Remote sensing of plant nitrogen status in corn. Trans. ASAE 39:1869–1875.

Blackburn, G.A. 1998. Quantifying chlorophyll and carotenoids at leaf and canopy scales: An evaluation of some hyperspectral approaches. Remote Sens. Environ. 66:273–285.

Blackburn, G.A. 1999. Relationships between spectral reflectance and pigment concentrations in stacks of deciduous broadleaves. Remote Sens. Environ. 70:224–237.

Boegh, E., H. Soegaard, N. Broge, C.B. Hasager, N.O. Jensen, K. Schelde, and A. Thomsen. 2002. Airborne multispectral data for quantifying leaf area index, nitrogen concentration, and photosynthetic efficiency in agriculture. Remote Sens. Environ. 81:179–193.

Carter, G.A. 1993. Responses of leaf spectral reflectance to plant stress. Am. J. Bot. 80:239–243.

Carter, G.A., W.G. Cibula, and R.L. Miller. 1996. Narrow-band reflectance imagery compared with thermal imagery for early detection of plant stress. J. Plant Physiol. 148:515–522.

Carter, C.A., and D.R. Young. 1993. Foliar spectral reflectance and plant stress on a barrier island. Int. J. Plant Sci. 154:298–305.

Colwell, J.E. 1974. Vegetation canopy reflectance. Remote Sens. Environ. 3:175–183.

Corwin, D.L., M.L.K. Carrillo, P.J. Vaughan, J.D. Rhoades, and D.G. Cone. 1999. Evaluation of a GIS-linked model of salt loading to groundwater. J. Environ. Qual. 28:471–480.

Datt, B., T.R. McVicar, T.G. van Niel, D.L.B. Jupp, and J.S. Pearlman. 2003. Preprocessing EO-1 hyperion hyperspectral data to support the application of agricultural indexes. IEEE Trans. Geosci. Remote Sens. 41:1246–1259.

Dehaan, R.L., and G.R. Taylor. 2002. Field-derived spectra of salinized soils and vegetation as indicators of irrigation-induced soil salinization. Remote Sens. Environ. 80:406–417.

Elvidge, C.D., and Z. Chen. 1995. Comparison of broad-band, narrow-band red, and near-infrared vegetation indices. Remote Sens. Environ. 54:38–48.

Grattan, S.R., C.M. Grieve, J.A. Poss, P.H. Robinson, D.L. Suarez, and S.E. Benes. 2004. Evaluation of salt-tolerant forages for sequential water reuse systems. I. Biomass production. Agric. Water Manage. 70:109–120.

Jacobsen, S.-E., H. Pedersen, and C.R. Jensen. 1998. Reflectance measurements, a quick and non-destructive technique for use in agricultural research. p. 1–5. *In* Int. Conf. on Sustainable Agric. in Tropical and Subtropical Highlands with Special Reference to Latin America (SATHLA), Rio de Janeiro. 9–13 Mar. 1998. Available at http://www.condesan.org/memoria/AGRO0198.pdf (verified 30 Mar. 2006). CONDENSAN, Lima.

Kaffka, S.R., D.L. Corwin, S.M. Lesch, and G.L. Fitzgerald. 2000. Field-scale soil electrical conductivity characteristics and sugarbeet emergence, growth, and yield. p. 17–29. *In* Proc. 2000 California Plant & Soil Conference: Farming in Crisis—Sustaining Agriculture in California, Stockton, CA. 18–20 Jan. 2000. ASA, Madison, WI.

Leblon, B., J. McRobert, V. Vanderbilt, and S. Thériault. 2001. Use of geomatics in precision agriculture. Available at http://www.digitalearth.ca/pdf/DE_A_283.PDF (verified 30 Mar. 2006). Canadian Institute of Geomatics, Ottawa.

Luther, J.E., and A.L. Carroll. 1999. Development of an index of balsam fir vigor by foliar spectral reflectance. Remote Sens. Environ. 69:241–252.

Maas, E.V., and S.R. Grattan. 1999. Crop Yields as affected by salinity. p. 55–108. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Méthy, M., R. Joffre, and S. Rambal. 1999. Remote sensing of canopy photosynthetic performances: Two complementary ways for assessing the photochemical reflectance index. Photosynthetica 37:239–247.

Peñuelas, J., I. Filella, C. Biel, L. Serrano, and R. Savé. 1993. The reflectance at the 950–970nm region as an indicator of plant water status. Int. J. Remote Sens. 14:1887–1905.

Peñuelas, J., and Y. Inoue. 1999. Reflectance indices indicative of changes in water and pigment contents of peanut and wheat leaves. Photosynthetica 36:355–360.

Peñuelas, J., J. Piñol, R. Ogaya, and I. Filella. 1997. Estimation of plant water concentration by the reflectance Water Index WI (R900/R970). Int. J. Remote Sens. 18:2869–2875.

Pinter, P.J., J.L. Hatfield, J.S. Schepers, E.M. Barnes, M.S. Moran, C.S.T. Daughtry, and D.R. Upchurch. 2003. Remote sensing for crop management. Photogramm. Eng. Remote Sens. 69:647–664.

Poss, J.A., W.B. Russell, P.J. Shouse, R.S. Austin, S.R. Grattan, C.M. Grieve, J.H. Leith, and L. Zeng. 2004. A volumetric lysimeter system (VLS): And alternative to weighing lysimeters for plant-water relations studies. Comput. Electron. Agric. 43:55–68.

Read, J.J., L. Tarpley, J.M. McKinion, and K.R. Reddy. 2002. Narrow-waveband reflectance ratios for remote estimation of nitrogen status in cotton. J. Environ. Qual. 31:1442–1452.

Rinehart, G.J., J.H. Baird, R.N. Calhoun, and O. Schabbenberger. 2002. Remote sensing of brown patch and dollar spot on creeping bentgrass and annual bluegrass turf using visible and near-infrared spectroscopy. Aust. Turfgrass Manage. 4.2:1–7.

SAS Institute. 1997. SAS/STAT software: Changes and enhancements through Release 6.12. SAS Inst., Cary, NC.

Schepers, J.S., T.M. Blackmer, W.W. Wilhelm, and M. Resende. 1996. Transmittance and reflectance measurements of corn leaves from plants with different nitrogen and water supply. J. Plant Physiol. 148:523–529.

Sims, D.A., and J.A. Gamon. 2002. Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. Remote Sens. Environ. 81:337–354.

Steddom, K., G. Heidel, D. Jones, and C.M. Rush. 2003. Remote detection of rhizomania in sugar beets. Phytopathology 93:720–726.

Tan, Q., H. Lin, Y. Zhao, T. Qingxi, and Z. Lanfeng. 2000. Vegetation spectral feature extraction model. *In* Proc. of the 21st Asian Conf. on Remote Sensing, Taipei, Taiwan. 4–8 Dec. 2000 GIS Development, Pradesh, India.

Wang, D., J.A. Poss, T.J. Donovan, M.C. Shannon, and S.M. Lesch. 2002b. Biophysical properties and biomass production of elephant grass under saline conditions. J. Arid Environ. 52:447–456.

Wang, D., C. Wilson, and M.C. Shannon. 2002a. Interpretation of salinity and irrigation effects on soybean canopy reflectance in visible and near-infrared spectrum domain. Int. J. Remote Sens. 23:811–824.

Wiegand, C.L., J.D. Rhoades, D.E. Escobar, and J.H. Everitt. 1994. Photographic and videographic observations for determining and mapping the response of cotton to soil salinity. Remote Sens. Environ. 49:212–223.

Zarco-Tejada, P.J., J.R. Miller, G.H. Mohammed, T.L. Noland, and P.H. Sampson. 2002. Vegetation stress detection through chlorophyll a + b estimation and fluorescence effect on hyperspectral imagery. J. Environ. Qual. 31:1433–1441.

Zarco-Tejada, P.J., J.C. Pushnik, S. Dobrowski, and S.L. Ustin. 2003. Steady-state chlorophyll a fluorescence detection from canopy derivative reflectance and double-peak red-edge effects. Remote Sens. Environ. 84:283–294.